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PROVISIONAL APPLICATION FOR PATENT COVER SHEET

This is a request for filing a PROVISIONAL APPLICATION FOR PATENT under 37 CFR 1.53(c).

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INVENTOR(S)

Given Name (first and middle [if any])	Family Name or Surname	Residence (City and either State or Foreign Country)
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☐ *Additional inventors are being named on the ______ separately numbered sheets attached hereto*

TITLE OF THE INVENTION (500 characters max)

METHOD AND APPARATUS FOR ACQUIRING INFORMATION OF OPTICAL INHOMOGENEITY IN SUBSTANCES

Direct all correspondence to: **CORRESPONDENCE ADDRESS**

☑ Customer Number 29344 → *Place Customer Number Bar Code Label here* 29344 PATENT & TRADEMARK OFFICE

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ENCLOSED APPLICATION PARTS ***(check all that apply)***

☑ Specification *Number of Pages* 20 ☐ CD(s), Number

☑ Drawing(s) *Number of Sheets* 11 ☐ Other (specify)

☐ Application Data Sheet. See 37 CFR 1.76

METHOD OF PAYMENT OF FILING FEES FOR THIS PROVISIONAL APPLICATION FOR PATENT

☐ Applicant claims small entity status. See 37 CFR 1.27.

☑ A check or money order is enclosed to cover the filing fees

☑ The Commissioner is hereby authorized to charge filing fees or credit any overpayment to Deposit Account Number: 50-1798

☐ Payment by credit card. Form PTO-2038 is attached.

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The invention was made by an agency of the United States Government or under a contract with an agency of the United States Government.

☑ No.

☐ Yes, the name of the U.S. Government agency and the Government contract number are: ______________

Respectfully submitted,

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Date 12/04/2003

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USE ONLY FOR FILING A PROVISIONAL APPLICATION FOR PATENT

PATENT
Attorney Docket No.: TOM-0003PR
Customer No.: 29344

IN THE UNITED STATES PATENT AND TRADEMARK OFFICE

Applicant(s): Feiling Wang
Filing Date: Herewith
Title: METHOD AND APPARATUS FOR ACQUIRING INFORMATION OF OPTICAL INHOMOGENEITY IN SUBSTANCES

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TRANSMITTAL LETTER

Enclosed herewith for filing in the above-identified provisional patent application please find the following listed items:

1. Provisional Application Cover Sheet;
2. Provisional Patent Application including twenty (20) pages of specification;
3. Eleven (11) pages of drawings;
4. Check in the amount of $160.00 to cover application filing fee; and
5. Return Postcard.

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Respectfully submitted,

Date: December 4, 2003

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Title: Method and Apparatus for Acquiring Information of Optical Inhomogeneity in Substances.

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Objects of Invention

The primary object of the present invention is to provide a method and apparatus for acquiring information regarding optical inhomogeneity in substance by a non-invasive means with the help of a low-coherence radiation.

A further object of the invention is to achieve high signal stability and high signal-to-noise ratio by eliminating the need of splitting the light radiation into a sample path and a reference path.

A yet further object of the invention is to provide a platform on which phase-resolved measurements such as birefringence and absolute refractive indices can be made.

A yet further object of the invention is to acquire optical inhomogeneity with regard to the spectral absorbance.

A yet further object of the invention is to solve the problem of signal drifting and fading caused by the polarization variation in conventional interferometers.

A yet further object of the invention is to make effective use of the source radiation with simple optical arrangements.

Background of Invention

Investigation of substances by non-invasive and optical means has been the object of many studies as inhomogeneity of light-matter interactions in substances can reveal their structural, compositional, physiological and biological information. Among existing techniques the optical coherence domain reflectometry, or OCDR, is of particular relevance to the present invention.

In OCDR, a light source of broad spectral distribution, often termed as broadband source, low-coherence source, partially coherent source or white light source, is generally employed. Referring to Fig. 1, a conventional approach is to

split the radiation of the source into two paths, one propagating to impinge on the substances under study, or sample, while the other propagating towards a reference surface. The radiations reflected from the sample and from the reference surface are then brought back to the same space and let interfere. Because of the wavelength-dependent phase delay the interference results in no observable interference fringes unless the two optical path lengths of the split radiations are very similar, a physical mechanism for ranging. If the same device is used for both splitting and recombining the radiation we speak of a Michelson interferometer. The discoveries and the theories of the interference of partially coherent light is summarized by Born and Wolf in "Principles of Optics", Pergamon Press, 1980.

Low-coherence light in free-space Michelson interferometers was first utilized for measurement purposes. With the advent of optical fibers modern interferometers are often constructed with fiber-optic components, leading to flexible application of low-coherence light as means of characterizing substances. Various embodiments of the fiber-optic OCDR exist such as what is disclosed by Sorin et al in US Patent No. 5,202,745, by Marcus et al in US Patent No. 5,659,392, by Mandella et al in US Patent No. 6,252,666, and by Tearney et al in US Patent No. 6,421,164. The application of OCDR in medical diagnoses has come to known as "optical coherence tomography", or OCT.

Common to all these embodiments, the radiation from the low-coherence source is first physically parted to have two portions, one traveling down a sample waveguide to interact with the sample while the other traveling down a reference waveguide. The reflected radiation from the sample is later recombined with the reference light from the reference waveguide and let interfere, as typified by the arrangement described in US Patent 6,421,164.

A disadvantage to these designs in the prior art stems from the separation of the reference light beam from the sample light beam. Due to the separation the relative optical phase, or differential delay, between the two beams cannot be easily maintained as each may experiences different physical length, vibration, temperature, waveguide bending and so on. When the sample arm is in the form of a fiber-based catheter, in particular, the manipulation of the fiber can cause very significant fluctuation and drift of the differential phase. The lack of stable differential phase between the two beam makes such phase sensitive measurements as absolute valuation of refractive indices and measurements of birefringence very difficult.

It is often beneficial to acquire the absorption characteristics of the material in an isolated volume inside the sample. In other case it is desirable to map the distribution of some substances identifiable through their characteristic spectral absorbance. Another shortcoming of the prior art is that they do not enable direct measurements of the optical inhomogeneity with regard to these spectral characteristics.

Description of Drawings

Fig. 1 shows the optical arrangement for the optical coherence domain reflectometry in the prior art.

Fig. 2 is a block diagram for an optical system for acquiring information regarding optical inhomogeneity in substances.

Fig. 3 shows an implementation of the optical system depicted in Fig. 2.

Fig. 4 depicts a possible construction of the probe head in the implementation shown in Fig. 3.

Fig. 5 is a block diagram for an alternative optical system for acquiring information regarding optical inhomogeneity in substances.

Fig. 6 shows an implementation of the optical system depicted in Fig. 5.

Fig. 7 depicts a possible construction of the probe head in the implementation shown in Fig. 6.

Fig. 8 depicts a design for the optical director used in the implementation shown in Fig. 6.

Fig. 9 is a block diagram for an optical system with the capability of acquiring information about inhomogeneity in substances with regard to the characteristics of spectral absorption.

Fig. 10 is a block diagram for another optical system with the capability of acquiring information about inhomogeneity in substances with regard to the characteristics of spectral absorption.

Fig. 11 depicts the spectral characteristics of the light source, the sample absorbance and the band pass filter involved in the systems shown in Fig. 9 and Fig. 10.

Description of Invention

The primary objective of the invention is accomplished through the use of the low-coherence nature of broadband light sources in a system depicted in Fig. 2. Light radiation from broadband light source **201** is coupled into the first dual-mode waveguide **271** to excite two orthogonal propagation modes, **001** and **002**. Light director **210** directs the two modes to the second dual-mode waveguide **272** that is terminated by probe head **220**. The first function of the probe head is to reverse the propagation direction of mode **001** in waveguide **272**; the second function of the probe head is to reshape and delivered the light in mode **002** to the sample **205**; and the third function of the probe head is to collect the light reflected from the sample back the second dual-mode waveguide **272**. The back traveling light in both modes is then directed by light director **210** to the third waveguide **273** and further propagates towards differential delay modulator **250**. The differential delay modulator is capable of varying the relative optical path length and optical phase between mode **001** and **002**. Finally detection subsystem **260** superpose the two propagation modes to form two new modes, mutually orthogonal, to be received by photo-detectors.

In the example shown in Fig. 2, the superposition of the two modes in the detection subsystem allows range detection. The light entering the detection subsystem in mode **002** is reflected by the sample, bearing information about the optical inhomogeneity of the sample, while the other mode, **001**, bypassing the sample inside probe head **220**. So long as these two mode remain independent through the waveguides their superposition in the detection subsystem yields the same information about the sample as with a conventional Michelson interferometer.

For the simplicity of the analysis, let us first consider a thin slice of the source spectrum by assuming that the amplitude of mode **001** is E_{001} and that of mode **002** is E_{002} in the first waveguide **271**. The sample can be characterized by an effective reflection coefficient r that is complex in nature; the differential delay modulator **350** can be characterized by a pure phase shift Γ exerted on mode **001**. Let us now superpose the two modes by projecting them onto a pair of new modes, represented by a 45 degree rotation in the vector space, we get

$$\begin{cases} E_A = \dfrac{1}{\sqrt{2}}(e^{j\Gamma}E_{001} + rE_{002}); \\ E_B = \dfrac{1}{\sqrt{2}}(e^{j\Gamma}E_{001} - rE_{002}). \end{cases} \tag{1}$$

In deriving the above equation it has been assumed that all components in the system, except for the sample, are lossless. The resultant intensities of the two superposed modes are

$$\begin{cases} I_A = \dfrac{1}{2}\left[E_{001}^2 + E_{002}^2 + |r| E_{001}E_{002}\cos(\Gamma - \varphi)\right]; \\ I_B = \dfrac{1}{2}\left[E_{001}^2 + E_{002}^2 - |r| E_{001}E_{002}\cos(\Gamma - \varphi)\right], \end{cases} \tag{2}$$

where φ is the phase delay associated with the reflection from the sample. A convenient way to characterize the reflection coefficient r is to measure the difference of the above two intensities, i.e.

$$I_A - I_B = |r| E_{001}E_{002}\cos(\Gamma - \varphi) . \tag{3}$$

If Γ is modulated by differential delay modulator **250**, the measured signal, Eq. (3), is modulated accordingly. For either a periodic or a time-linear variation of Γ, the measured responds with a periodic oscillation, its peak-to-peak value being proportional to the absolute value of r.

For a broadband light source, we must consider the two phases, Γ and φ, wavelength dependent. If the two modes experience significantly different path lengths when they reach the detection system, the overall phase angle, Γ - φ, must be significantly wavelength dependant as well. Consequently the measured signal, being an integration of Eq. (3) over the source spectrum, yields a smooth function even though Γ is being varied. The only condition for a significant oscillation to occur in the measured is when the two modes experience very similar path lengths at the point of their superposition. In this case the overall phase angle, Γ - φ, becomes wavelength independent or nearly wavelength independent. In other words, for a given relative path length set by **250**, an oscillation in the measured signal indicates a reflection, in the other mode, from a distance that equalizes the optical path lengths traveled by the two modes. Therefore the system depicted in Fig. 2 can be utilized for ranging reflection sources.

Due to the stability of relative phase between the two modes, **001** and **002**, phase-sensitive measurements can be performed with the invented system with

relative ease. The following describes a scheme for the determination of the absolute phase associated with the radiation reflected from the sample.

The scheme involves generating a sinusoidal modulation in the differential phase by means of differential delay modulator **250**, with magnitude M and frequency Ω, so that we can rewrite the measured as follows:

$$I_A - I_B = |r| E_{001} E_{002} \cos[M \sin(\Omega t) - \varphi]\,. \tag{4}$$

It is clear from Eq. (4) that the measured exhibits an oscillation form that contains a base frequency of Ω and its harmonics. The amplitudes of the base frequency and each of the harmonics are related to φ and $|r|$. It is straightforward to derive the mathematical expressions for the relationships between r and the harmonics. For instance, the amplitude of the base-frequency oscillation and the second harmonic can be found from Eq. (4) to be:

$$A_\Omega = E_{001} E_{002} J_1(M) |r| \sin\varphi\,; \tag{5a}$$

$$A_{2\Omega} = E_{001} E_{002} J_2(M) |r| \cos\varphi\,, \tag{5b}$$

where J_1 and J_2 are Bessel functions of the first and second order, respectively. From Eq. (5a) and (5b) one can solve for $|r|$ and φ, i.e. the complete characterization of r. We can therefore completely characterize the complex reflection coefficient r by analyzing the harmonic content of various orders in the measured signal. In particular, the presence of the base-frequency component in the measured is due to the presence of φ.

An implementation of the system depicted in Fig. 2 is shown in Fig. 3. The spectrum of source **201** should be chosen to satisfy the desired ranging resolution. The broader the spectrum is the better the ranging resolution. Some semiconductor superluminescent light emitting diodes (SLED) and amplified spontaneous emission (ASE) sources may possess the appropriate spectral properties for the purpose. Polarization controller **302** is used to control the state of polarization in order to proportion the magnitudes of the two modes, **001** and **002**, in waveguide **371**. Dual-mode waveguides **371**, **372** and **373** are capable of supporting two independent polarization modes which are mutually orthogonal. One kind of practical and commercially available waveguide is the polarization maintaining optical fiber. A polarization maintaining fiber can carry two independent polarization modes, namely, the s-wave polarized along its slow axis and the p-wave polarized along its fast axis. In good quality polarization maintaining fibers these two modes have virtually no energy exchange, or coupling, for very substantial distances.

Polarization preserving circulator **310** directs the flow of optical waves according to the following scheme: the two incoming polarization modes from fiber **371** are directs to fiber **372**; the two incoming polarization modes from fiber **372** are directed to fiber **373**. Polarization-preserving circulator **310** is ideally required to maintain the separation of the two independent polarization modes. For instance, the s-wave in fiber **371** should be directed to fiber **372** as s-wave or p-wave only. Certain commercially available polarization-preserving circulators are adequate for the purpose.

The details of the probe head is shown in Fig. 4. Lens system **321** is to concentrate the light energy into a small area, facilitating spatially resolved studies of the sample in a lateral direction. Polarizing beam splitter **423** is used to transmit radiation in one polarization mode, **002** shown, to the sample while diverting the other to reflector **424**, that can be simply a coating on one side of beam splitter **423**. Reflector **424** should be aligned to allow the reflected radiation to re-enter polarization-maintaining fiber **372**.

A number of hardware choices are available for differential delay modulator **250**, either mechanical or non-mechanical. A non-mechanical type may consist of one or more segments of tunable birefringent materials such as liquid crystal materials and lithium niobate crystals in conjunction with fixed birefringent materials such as quartz and rutile. A mechanical device can be constructed by first separating the radiation by polarization mode with a polarizing beam splitter, one polarization mode propagating through a fix path while the other propagating through a variable path consisting of a piezoelectric stretcher of polarization maintaining fibers, or a pair of collimators both facing a mechanically movable retroreflector in such a way that the light from one collimator is collected by the other through a trip to and from the retroreflector, or a pair collimators optically linked through double passing a rotatable optical plate and bouncing off a reflector.

Superposition of the two independent polarization modes in the detection subsystem occurs when the two modes reach polarization beam splitter **361**. Beam splitter **361** is preferably oriented in such a way that, for each independent polarization mode, the two split portions possess the same amplitude. This way, each photo-detector receives a superposed mode characterized by Eq. (1). This can be accomplished by rotating polarizing beam splitter **361** so that the incident plane of its reflection surface make a 45 degree angle with one of the two independent polarization mode, **001** or **002**.

To use the above-mentioned optical system for measuring and displaying the optical inhomogeneity of a substance one needs to add control electronics. Differential delay modulator **250**, under the control of the electronics and programs, generates a form of differential phase modulation as the differential path length scans through a range that matches a range of depth inside the sample. The electronic controller is also programmed to record and extract the amplitude of the oscillation in the measured signal characterized by Eq. (3) at various differential path lengths generated by **250**. One thus acquires a profile of reflection as a function of depth, a one-dimensional representation of sample inhomogeneity.

For acquiring two-dimensional images of optical inhomogeneity in the sample, the probe head should be controlled so that the probe beam scans in a lateral direction, perpendicular to the light propagation direction. For every increment of the lateral scan a profile of reflection as a function of depth can be recorded with the method described above. The collected information can then be displayed to form a cross-sectional image that reveals the inhomogeneity of the sample.

Alternative to the design shown in Fig. 2, the optical arrangement depicted in Fig. 5 can be utilized for the same purpose. In this arrangement radiation from light source **201** is coupled to one mode supported by mode maintaining waveguide **571**. Light director **510** serves similar functions as **210** to convey the mode from **571** to one of the two modes supported by dual-mode waveguide **271**. Dual-mode waveguide **271** is terminated at the other end by probe head **530** that performs these functions: a) to reverse the propagation direction of a small portion of the incoming radiation in mode **001**; b) to reshape the remaining radiation and transmit it to the sample; and c) to convert the radiation reflected from the sample to an independent mode, **002** shown, supported by dual-mode waveguide **272**. Now there are two modes propagating away from the probe head, mode **001** that bypasses the sample and mode **002** that originates from sample reflection, in complete analogy to what occurs in the system shown in Fig. 2. The rest of components in this system also function the same way as their counterparts in Fig. 2.

This alternative design, shown in Fig.5, can be implemented with practical components in an arrangement depicted by Fig. 6. Radiation from broadband light source **205** is further polarized and controlled by polarization controller **602** so that a polarization mode is excited in polarization-maintaining fiber **371**. Light director **610** conveys the polarization mode to one of the two polarization modes supported by polarization-maintaining fiber **372**. This mode further propagates towards the probe head **530**. One of the possible designs for the probe head **530** is

depicted Fig. 7. In this design, the termination of polarization-maintaining fiber **372** is used as partial reflector **632**. An uncoated termination of an optical fiber reflects approximately 4% of the light energy. Coatings can be used to alter the reflectivity of the termination to a desirable value. Lens system **731** reshapes and delivers the remaining radiation to sample **205**. The other role played by lens system **731** is to collect the radiation reflected from sample **205** back into polarization-maintaining fiber **372**. Quarter wave plate **733** is oriented so that its optical axis make a 45 degrees angle with the polarization direction of the transmitted light. Reflected light from the sample propagates through **733** once again to become polarized in a direction perpendicular to mode **001**, i.e. mode **002**. Quarter wave plate **733** can be replaced by a Faraday rotator.

Because there is only one polarization mode enters polarization-preserving circulator **610** from waveguide **371**, circulator **610** can be constructed with more common optical components as shown in Fig. 8. Polarization-maintaining circulator **811** is require to convey only one polarization mode among its three ports, rather than both modes as in the case shown in Fig. 3. Two additional polarizing beam splitter **812** and **813** are coupled to polarization-maintaining **811** so that both polarization modes entering Port 2 are conveyed to Port 3 and remain independent.

In cases it is beneficial to obtain information about certain substances, identifiable through their spectral absorbance, dispersed in the samples. For this purpose a tunable bandpass filter is added to the systems, as shown in Fig. 2 and Fig. 5. The role of the tunable bandpass filter is to allow a variable portion of the source spectrum to pass while measuring the distribution of the complex reflection coefficient with the method described previously.

Referring to Fig. 9, let us assume that we would like to acquire the absorption characteristics of a layer bounded by interfaces I and II. For the simplicity of description let us assume that the spectral absorption of the substance in the layer is characterized by a wavelength dependent attenuation coefficient $\mu_h(\lambda)$ and that of other volume is characterized by $\mu_g(\lambda)$. Let us further assume that the substance in the vicinity of interface *I* (*II*) possesses an effective and wavelength independent reflection coefficient r_I (r_{II}). If the characteristic absorption of interest is covered by the spectrum of the light source we can use a filter with bass band tunable across the characteristic absorption as shown in Fig. 11. First, one should adjust differential delay modulator **250** so that the path length traveled by mode **001** matches that of radiation reflected from interface I in mode **002**. At this point one can scan the pass band of filter **903** while recording the oscillation of the measured signal due

to a periodic differential phase generated by 250. The oscillation amplitude as a function of wavelength is given by

$$A_I(\lambda)=r_I e^{-2\mu_g(\lambda)z_I} \tag{6}$$

where z_I is the distance of interface I measured from the top surface of the sample. Now if we readjust differential delay modulator 250 so that the path length traveled by mode 001 matches that of radiation reflected from interface II in mode 002 and repeat the measurements, we get

$$A_{II}(\lambda)=r_{II} e^{-2\mu_g(\lambda)z_I-2\mu_h(\lambda)z_{II}} \quad , \tag{7}$$

where z_{II} is the distance of interface II measured from interface I. To acquire the absorption characteristics of the layer of interest one can divide Eq. (7) by Eq. (6) to obtain

$$\frac{A_{II}(\lambda)}{A_I(\lambda)}=\frac{r_{II}}{r_I}e^{-2\mu_h(\lambda)z_{II}} \quad . \tag{8}$$

We have thus acquired, with Eq. (8), the absorption characteristics of the layer of interest only.

It should be noted that the pass band of the filter should be narrow enough to resolve the absorption characteristics of interest and at the meantime broad enough to differentiate the layer of interest. Let us take an example to see whether this is reasonable and practical.

It is known that some predominant glucose absorption peaks in blood reside in a wavelength range between 1 and 2.5 microns. The width of these peaks are approximately 150 nm. To resolve the peaks we can choose the bandwidth of the tunable bandpass filter to be around 30 nm. The depth resolution is determined by the following equation:

$$\frac{2\ln(2)}{\pi}\frac{\lambda_o^{\ 2}}{\Delta\lambda}=60\mu m \tag{9}$$

Therefore, using the system depicted in Fig. 9 one can determine the absorption characteristics of the glucose in tissue layers no less than 60 μm thick. It is well known that human skin consists of a superficial epidermis layer that is typically 0.1 mm thick. Underneath epidermis is the dermis, approximately 1 mm

thick, where glucose concentrates in blood and interstitial fluids. The above analysis indicates that it is possible for us to use the apparatus shown in Fig. 9 to isolate the absorption characteristics of the dermis from that of the epidermis and other layers.

It is clear from Eq. (9) that the product of spectral resolution and layer resolution is a constant for a given center wavelength λ_0. The choice of the filter bandwidth should be made based on the tradeoff between these two resolutions against the specific requirements of the measurement.

A tunable bandpass filter can also be added to the optical system depicted in Fig. 5, as shown in Fig. 10. It can be operated the sample way as described above to acquire the absorption characteristics of an isolated volume inside a sample.

In all the above-mentioned optical designs and implementations there is a common and important feature, i.e. both the sample light and reference light, in the form of two independent modes, travel in the same waveguides except for the extra distance traveled by the probing light between the probe head and the sample. This feature stabilizes the relative phase, or differential optical path, between the sample light and the reference light, even in the presence of mechanical movement of the waveguides. This is in contrast to conventional interferometers in which sample light and reference light travel in different optical paths, prone to noise caused by the variation in the differential optical path. The stability of the differential optical path, achieved in the invented system, is beneficial for some phase-sensitive measurement, such as the determination of the absolute reflection phase and birefringence.

What Is Claimed Is:

1. An apparatus for acquiring information of optical inhomogeneity in substances, said apparatus comprising:

   a) a light source,

   b) a waveguide that is capable of supporting at least two independent propagation modes, said waveguide carrying the light radiation from said light source to the vicinity of a sample under examination,

   c) a probe head that terminates said waveguide in the vicinity of said sample and reverses the propagation direction of a first mode in said waveguide while transmitting a second mode to said sample,

d) a differential delay modulator that varies the relative optical path length between said first mode and said second mode supported by said waveguide,

e) a mode combiner that superposes said first mode and said second mode by converting a portion of each said mode to a pair of new modes,

f) a photo-detector or a plurality of photodetectors,

g) an electronic controller in communication with said probe head, said differential delay modulator and said photo-detectors.

2. An apparatus for acquiring information of optical inhomogeneity in substances, said apparatus comprising:

a) a light source that emits radiation to excite two independent propagation modes in a first waveguide capable of supporting at lease two independent propagation modes,

b) a light director that terminates the first waveguide with a first port and passes the light modes entering said first port, at least in part, through a second port and passes the light modes entering said second port, at least in part, through a third port,

c) a second waveguide that supports at least two independent propagation modes and links the second port of the light director to

d) a probe head that terminates the second waveguide and, in the vicinity of the sample, reverse the propagation direction of one mode while reshaping and delivering the other mode to the sample and gathering the reflected light from the sample back into the second waveguide,

e) a differential delay modulator that connects to the third port of the light director through a third waveguide capable of supporting at least two independent propagation modes and imposes a variable path length and a variable phase delay on one mode relative to the other before conveying both modes, through a fourth waveguide capable of supporting at least two independent modes, to

f) a detection subsystem that superposes the two propagation modes from the differential delay modulator to form two new modes, mutually orthogonal; said two new modes are terminated by two photo-detectors.

3. The apparatus of Claim 2 wherein all the four waveguides are polarization-maintaining optical fibers capable of supporting two orthogonal polarization modes.

4. The apparatus of Claim 2 wherein the first, the third and the fourth waveguides are free space while the second waveguide is a polarization-maintaining optical fiber capable of supporting two orthogonal polarization modes.

5. The apparatus of Claim 2 wherein all waveguides are free space.

6. The apparatus of Claim 2 wherein the probe head comprises a lens, a polarizing beam splitter and a reflector, arranged in such a way that said polarizing beam splitter diverts a first polarization mode to a reflector, causing it to re-enter the second waveguide, while transmitting a second polarization mode to the sample and collecting the reflected radiation from the sample back the second waveguide.

7. The apparatus of Claim 2 wherein the differential delay modulator consists of one or more segments of such tunable birefringent materials as liquid crystal materials and lithium niobate crystals in conjunction with such fixed birefringent materials as quartz and rutile.

8. The apparatus of Claim 2 wherein the differential delay modulator comprises a means of separating the radiation by modes and directing one through a fix path while directing the other through a variable path length device.

9. The apparatus of Claim 8 wherein the variable path length device is a piezoelectric stretcher of a polarization-maintaining optical fiber.

10. The apparatus of Claim 8 wherein the variable path length device comprises two collimators both facing a mechanically movable retroreflector in such a way that the collimated light from one collimator is collected by the other through a trip to and from the retroreflector.

11. The apparatus of Claim 8 wherein the variable path length device comprises two collimators optically linked through double passing a rotatable optical plate and bouncing off a reflector.

12. The apparatus of Claim 2 wherein the light director is a polarization-preserving circulator that conveys the independent modes supported by the first waveguide to the corresponding independent modes supported by the second waveguide without substantial mixing or cross coupling of modes and conveys the independent modes supported by the second waveguide to the corresponding

independent modes supported by the third waveguide without substantial mixing or cross coupling of modes.

13. The apparatus of Claim 2 wherein the light director is a polarization insensitive beam splitter.

14. The apparatus of Claim 2 wherein the detection subsystem comprises a polarizing beam splitter and two photo-detectors, said polarizing beam splitter oriented in such a way that each split radiation is a superposition of the two independent propagation modes in the fourth waveguide and is received by a photo-detector.

15. An apparatus for acquiring information of optical inhomogeneity in substances, said apparatus comprising:

a) a broadband and polarized light source that is optically coupled to a first polarization-maintaining fiber capable of supporting two orthogonal polarization modes,

b) a three-port polarization-preserving circulator that relays two orthogonal polarization modes entering a first port to a second port while relaying two orthogonal polarization modes entering said second port to a third port, said first port terminating the first polarization-maintaining fiber,

c) a second polarization-maintaining fiber that supports two orthogonal polarization modes; said second polarization-maintaining fiber is terminated at one end by the second port of the polarization-preserving circulator and at the other by

d) a probe head that comprises a lens, a polarizing beam splitter and a retroreflector, arranged in such a way that said polarizing beam splitter reverses the propagation direction of one polarization mode by diverting it to said retroreflector while reshaping and delivering the other polarization mode to the sample and gathering the reflected light from the sample back the second polarization-maintaining fiber,

e) a differential delay modulator that imposes a variable path length and a variable phase delay on one propagation mode in reference to the other; said differential delay modulator is linked at one end to the third port of the light director and at the other to

f) a detection subsystem comprising a polarizing beam splitter and two photo-detectors; said polarizing beam splitter oriented in such a way

that each split light wave is a superposition of the two polarization modes leaving the third port of the polarization-preserving circulator and is received by a photo-detector.

16. The apparatus of Claim 15 wherein the differential delay modulator consists of one or more segments of such tunable birefringent materials as liquid crystal materials and lithium niobate crystals in conjunction with such fixed birefringent materials as quartz and rutile.

17. The apparatus of Claim 15 wherein the differential delay modulator comprises a means of separating the radiation by modes and directing one through a fix path while directing the other through a variable path length device.

18. The apparatus of Claim 17 wherein the variable path length device is a piezoelectric stretcher of a polarization-maintaining optical fiber.

19. The apparatus of Claim 17 wherein the variable path length device comprises two collimators both facing a mechanically movable retroreflector in such a way that the collimated light from one collimator is collected by the other through a trip to and from the retroreflector.

20. The apparatus of Claim 17 wherein the variable path length device comprises two collimators optically linked through double passing a rotatable optical plate and bouncing off a reflector.

21. An apparatus for acquiring information of optical inhomogeneity in substances, said apparatus comprising:

   a) a light source,

   b) a waveguide that is capable of supporting at least two independent propagation modes, said waveguide carrying the light radiation from said light source to the vicinity of a sample under examination,

   c) a probe head that terminates said waveguide in the vicinity of said sample and reverses the propagation direction of a portion of a first mode in said waveguide while transmitting the remainder to said sample meanwhile converting the reflected light collected from said sample to a second propagation mode,

   d) a differential delay modulator that varies the relative optical path length between said first mode and said second mode supported by said waveguide,

e) a mode combiner that superposes said first mode and said second mode by converting a portion of each said mode to a pair of new modes,

f) a photo-detector or a plurality of photodetectors,

g) an electronic controller in communication with said probe head, said differential delay modulator and said photo-detectors.

22. An apparatus for acquiring distribution of optical inhomogeneity in substances, said apparatus comprising:

a) a light source that emits radiation to excite a propagation mode in a first waveguide capable of maintaining the mode,

b) a light director that terminates the first waveguide with its first port and passes the light mode entering said first port, at least in part, through a second port and passes the light modes entering said second port, at least in part, through a third port,

c) a second waveguide that supports at least two independent propagation modes and links the second port of the light director to

d) a probe head that reverses the propagation direction of the light in part and transmits the remainder to the sample meanwhile transforming the collected light from the sample reflection to an orthogonal mode supported by the second waveguide,

e) a differential delay modulator that connects to the third port of the light director through a third waveguide capable of supporting at least two independent propagation modes and imposes a variable phase delay and a variable path length on one mode in reference to the other before conveying both modes, through a fourth waveguide capable of supporting at least two independent modes, to

f) a detection subsystem that superposes the two propagation modes from the fourth waveguide to form two new modes, mutually orthogonal; said two new modes are terminated by two photo-detectors.

23. The apparatus of Claim 22 wherein all the four waveguides are polarization-maintaining optical fibers capable of supporting two orthogonal polarization modes.

24. The apparatus of Claim 22 wherein the first, third and fourth waveguides are free space while the second waveguide is a polarization-maintaining optical fiber capable of supporting two orthogonal polarization modes.

25. The apparatus of Claim 22 wherein all waveguides are free space.

26. The apparatus of Claim 22 wherein the probe head consists of an uncoated or coated termination of a polarization-maintaining fiber to have a finite reflectance, a lens and a quarter-wave plate or a Faraday rotator, all in a series.

27. The apparatus of Claim 22 wherein the differential delay modulator consists of one or more segments of such tunable birefringent materials as liquid crystal materials and lithium niobate crystals in conjunction with such fixed birefringent materials as quartz and rutile.

28. The apparatus of Claim 22 wherein the differential delay modulator comprises a means of separating the radiation by modes and directing one through a fix path while directing the other through a variable path length device.

29. The apparatus of Claim 28 wherein the variable path length device is a piezoelectric stretcher of a polarization-maintaining optical fiber.

30. The apparatus of Claim 28 wherein the variable path length device comprises two collimators both facing a mechanically movable retroreflector in such a way that the collimated light from one collimator is collected by the other through a trip to and from the retroreflector.

31. The apparatus of Claim 28 wherein the variable path length device comprises two collimators optically linked through double passing a rotatable optical plate and bouncing off a reflector.

32. The apparatus of Claim 22 wherein the light director is a polarization-preserving circulator that conveys a mode supported by the first waveguide to one of the modes supported by the second waveguide and conveys the independent modes supported by the second waveguide to the corresponding independent modes supported by the third waveguide.

33. The apparatus of claim 22 wherein the light director comprises:

a) a polarization-maintaining circulator that conveys a polarization mode entering a first port to a second port, causing no change in the state of polarization, and conveys the polarization mode entering said second port to a third port, causing no change in the state of polarization,

b) a first polarizing beam splitter that is connected to the second port of the polarization-maintaining circulator and separates the light into two different paths by state of polarization, and

c) a second polarizing beam splitter that is connected to the third port of the polarization-maintaining circulator and separates the light into two different paths by state of polarization.

34. The apparatus of Claim 22 wherein the light director is a polarization-insensitive beam splitter.

35. The apparatus of Claim 22 wherein the detection subsystem comprises a polarizing beam splitter oriented in such a way that each split radiation is a superposition of the two independent propagation modes in the fourth waveguide and is received by a photo-detector.

36. An apparatus for acquiring distribution of optical inhomogeneity in substances, said apparatus comprising:

a) a broadband and polarized light source that is optically coupled to one of the polarization modes supported by a first polarization-maintaining fiber,

b) a polarization-preserving circulator that conveys a polarization mode entering a first port linked to the first polarization-maintaining fiber to a second port linkable to a polarization-maintaining fiber and conveys two orthogonal polarization modes entering said second port to a third port linkable to a polarization maintaining fiber without appreciable mode mixing or coupling,

c) a second polarization-maintaining fiber that supports two orthogonal polarization modes; said second polarization-maintaining fiber is terminated at one end by the second port of the polarization-preserving circulator and at the other by

d) a probe head that comprises an uncoated or coated termination of the second polarization-maintaining fiber to have a finite reflectance, a lens and a quarter-wave plate or a Faraday rotator arranged in a series,

e) a differential delay modulator that imposes a variable path length and a variable phase delay on one propagation mode in reference to the other; said differential delay modulator is linked at one end to the third port of the light director and at the other to

f) a detection subsystem comprising a polarizing beam splitter and two photo-detectors; said polarizing beam splitter oriented in such a way that each split light wave is a superposition of the two polarization

modes leaving the third port of the polarization-preserving circulator and is received by a photo-detector.

37. The apparatus of Claim 36 wherein the differential delay modulator consists of one or more segments of such tunable birefringent materials as liquid crystal materials and lithium niobate crystals in conjunction with such fixed birefringent materials as quartz and rutile.

38. The apparatus of Claim 36 wherein the differential delay modulator comprises a means of separating the radiation by modes and directing one through a fix path while directing the other through a variable path length device.

39. The apparatus of Claim 38 wherein the variable path length device is a piezoelectric stretcher of a polarization-maintaining optical fiber.

40. The apparatus of Claim 38 wherein the variable path length device comprises two collimators both facing a mechanically movable retroreflector in such a way that the collimated light from one collimator is collected by the other through a trip to and from the retroreflector.

41. The apparatus of Claim 38 wherein the variable path length device comprises two collimators optically linked through double passing a rotatable optical plate and bouncing off a reflector.

42. The apparatus of Claim 1, further comprising a tunable band pass filter, inserted in one of the four waveguides.

43. The apparatus of Claim 2, further comprising a tunable band pass filter, inserted in one of the four waveguides.

44. The apparatus of Claim 15, further comprising a tunable band pass filter, inserted in one of the four polarization-maintaining fibers.

45. The apparatus of Claim 21, further comprising a tunable band pass filter, inserted in one of the four waveguides.

46. The apparatus of Claim 22, further comprising a tunable band pass filter, inserted in one of the four waveguides.

47. The apparatus of Claim 36, further comprising a tunable band pass filter, inserted in one of the four polarization-maintaining fibers.

48. The apparatus of Claim 43 wherein the source spectrum covers some characteristic absorption peaks of glucose in an infrared wavelength range for the determination of glucose concentration in the dermis layer of human skin.

49. The apparatus of Claim 46 wherein the source spectrum covers some characteristic absorption peaks of glucose in an infrared wavelength range for the determination of glucose concentration in the dermis layer of human skin.

Prior Art

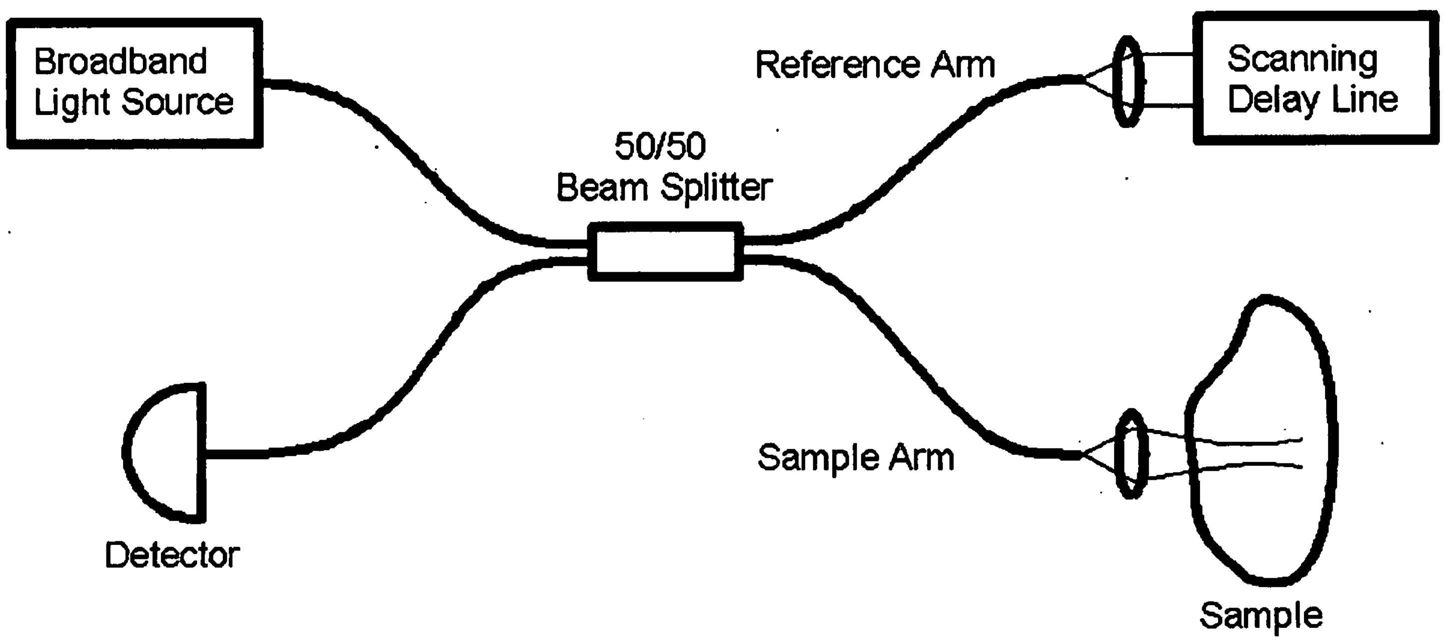
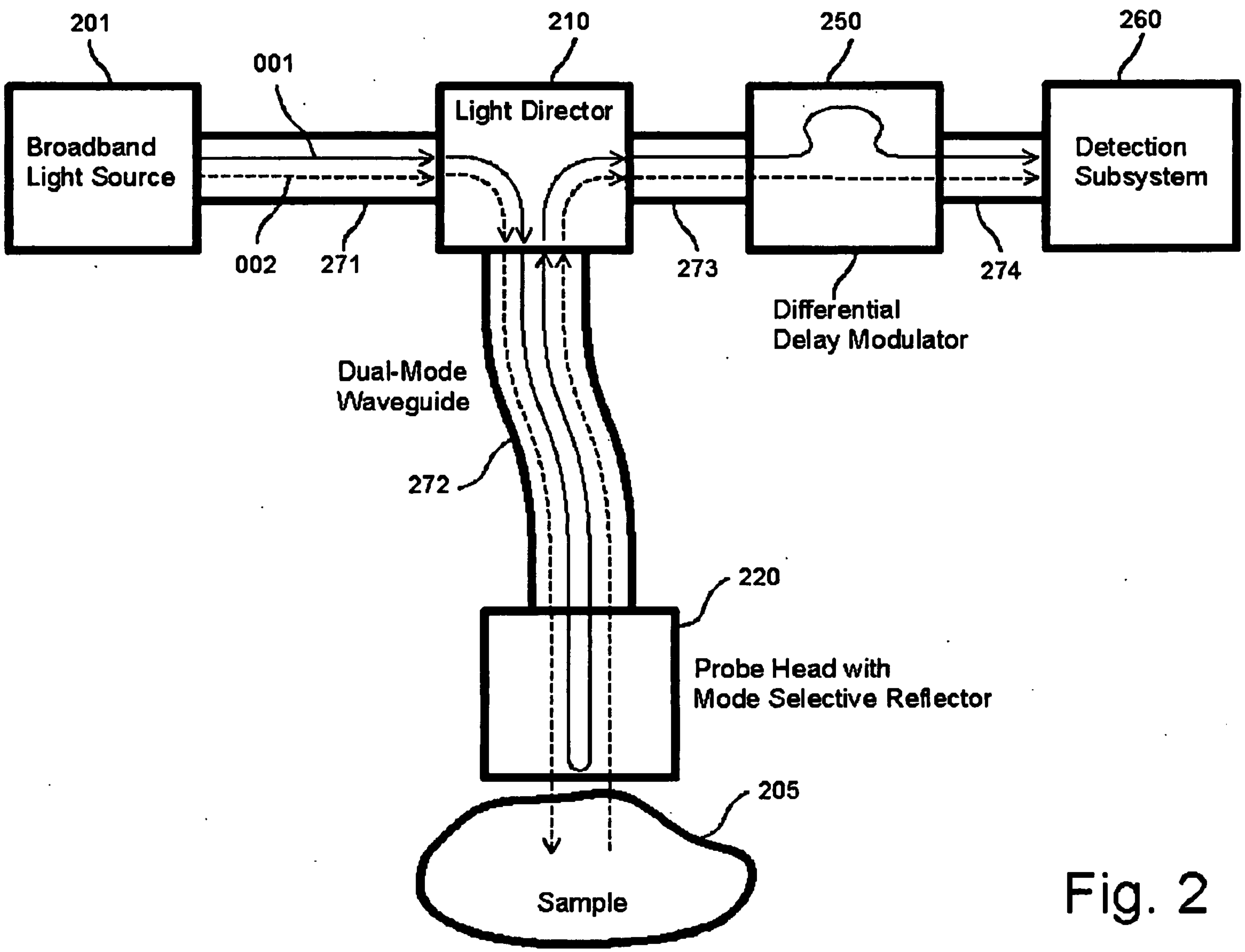


Fig. 1



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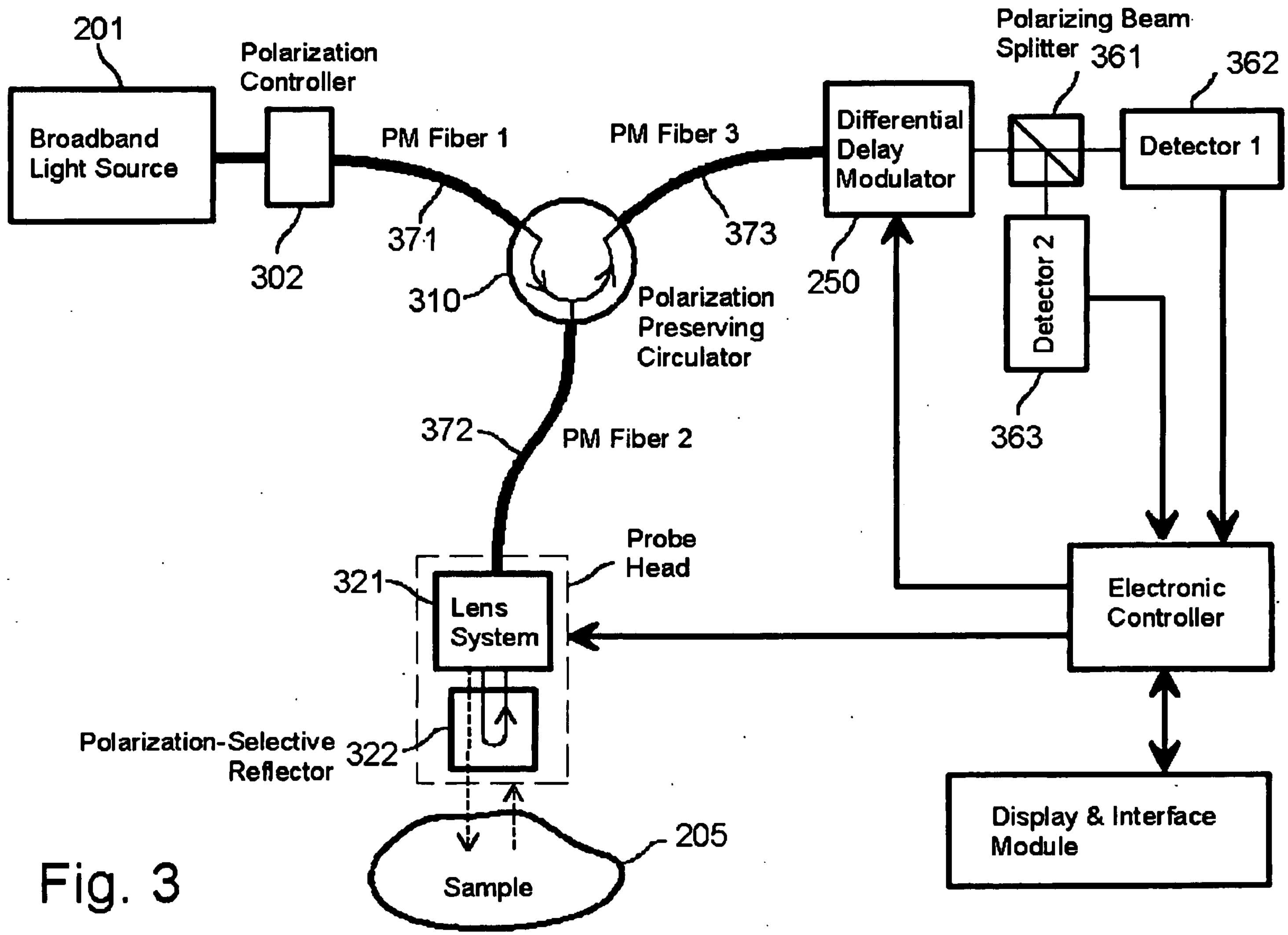
001
002
271
210
Light Director
273
250
Differential
Delay Modulator
274
260
Detection
Subsystem
Dual-Mode
Waveguide
272
220
Probe Head with
Mode Selective Reflector
205
Sample

Fig. 2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PM Fiber 1
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Preserving
Circulator
PM Fiber 3
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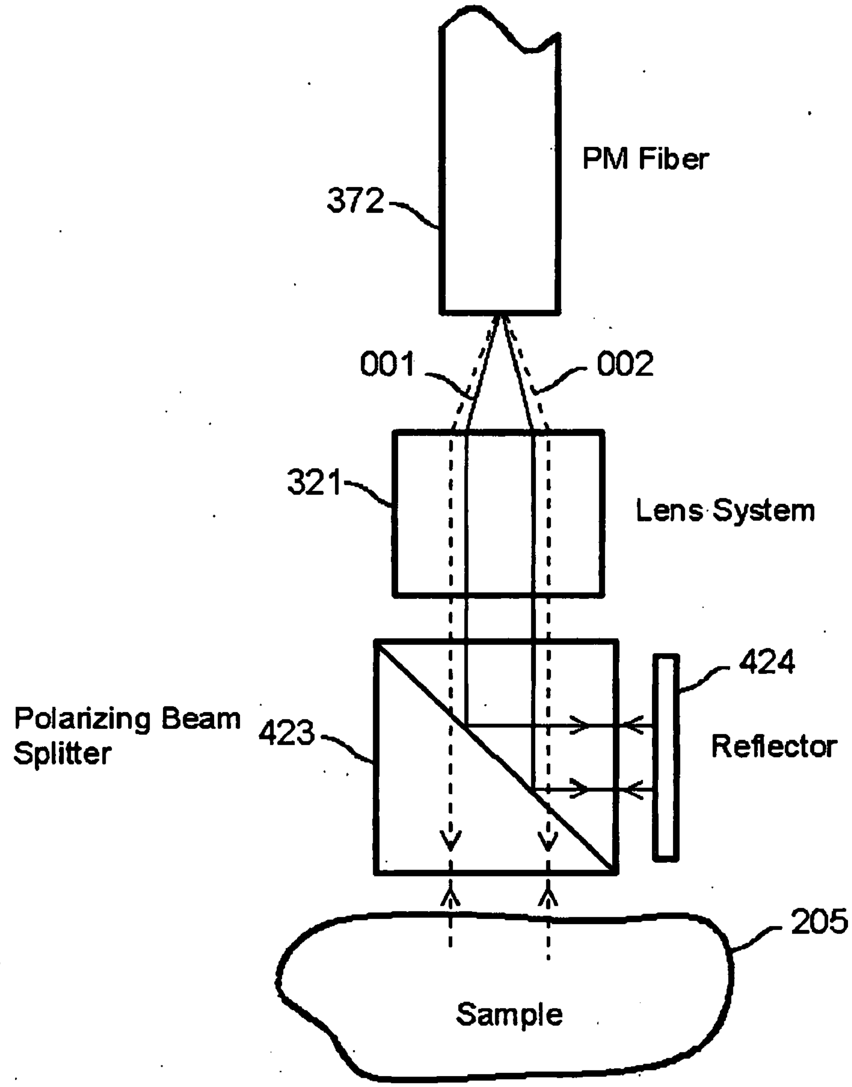
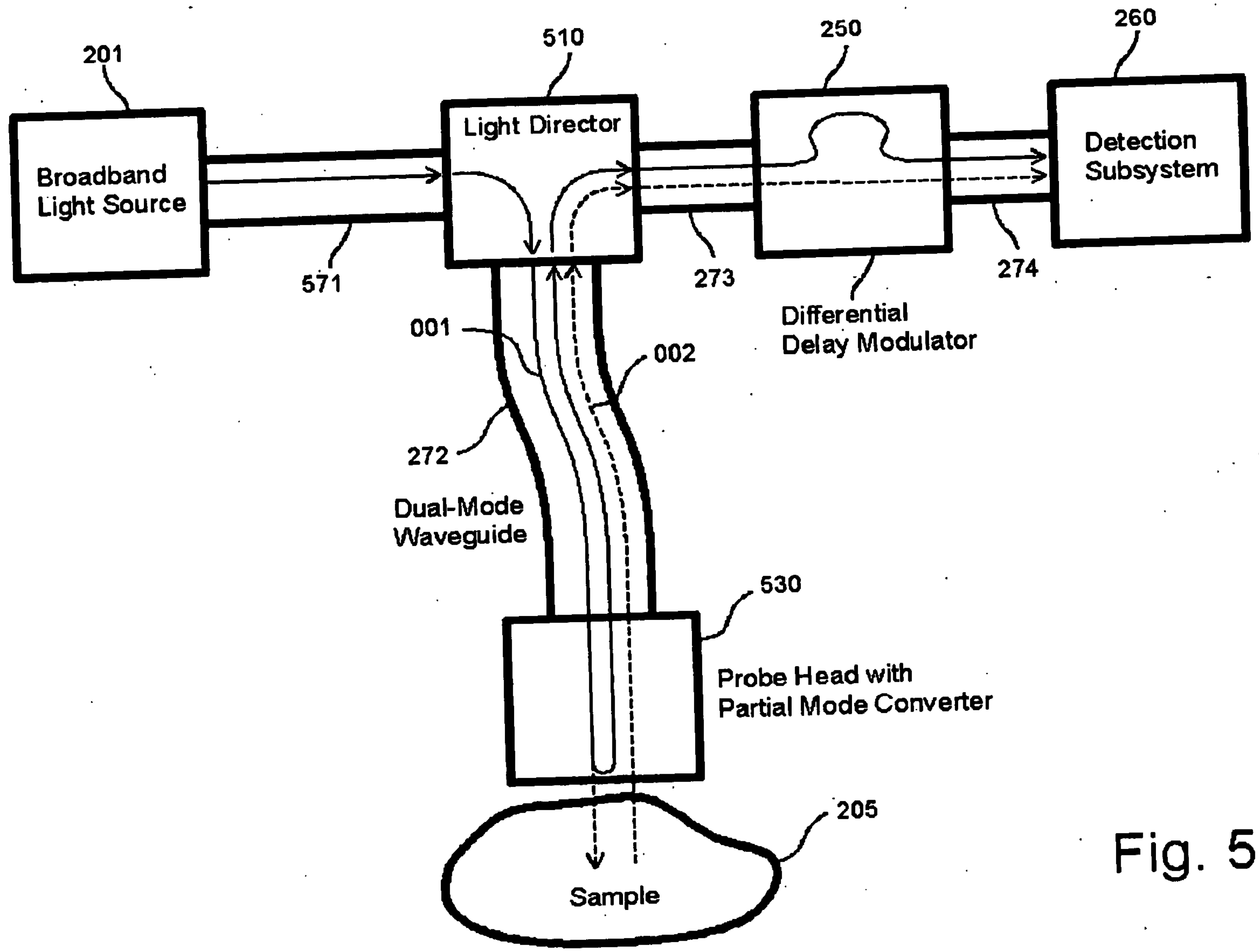
Delay
Modulator
250
Polarizing Beam
Splitter 361
362
Detector 1
Detector 2
363
372
PM Fiber 2
Probe
Head
321
Lens
System
Polarization-Selective
Reflector
322
205
Sample
Electronic
Controller
Display & Interface
Module

Fig. 3



PM Fiber
372
001
002
321
Lens System
424
Polarizing Beam Splitter
423
Reflector
205
Sample

Fig. 4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Light Director
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Dual-Mode
Waveguide
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Differential
Delay Modulator
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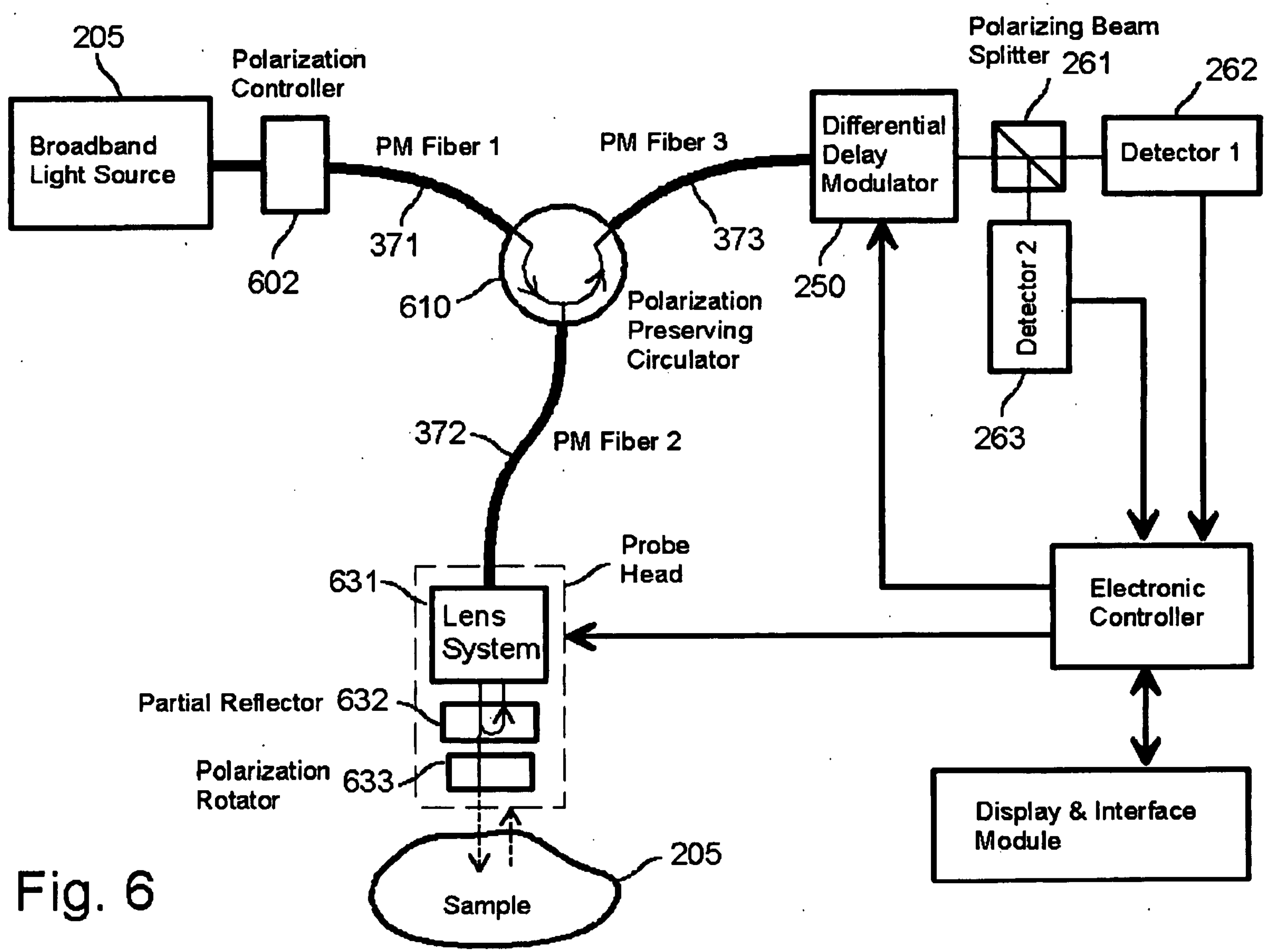
260
Detection
Subsystem
530
Probe Head with
Partial Mode Converter
205
Sample

Fig. 5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Polarization Controller
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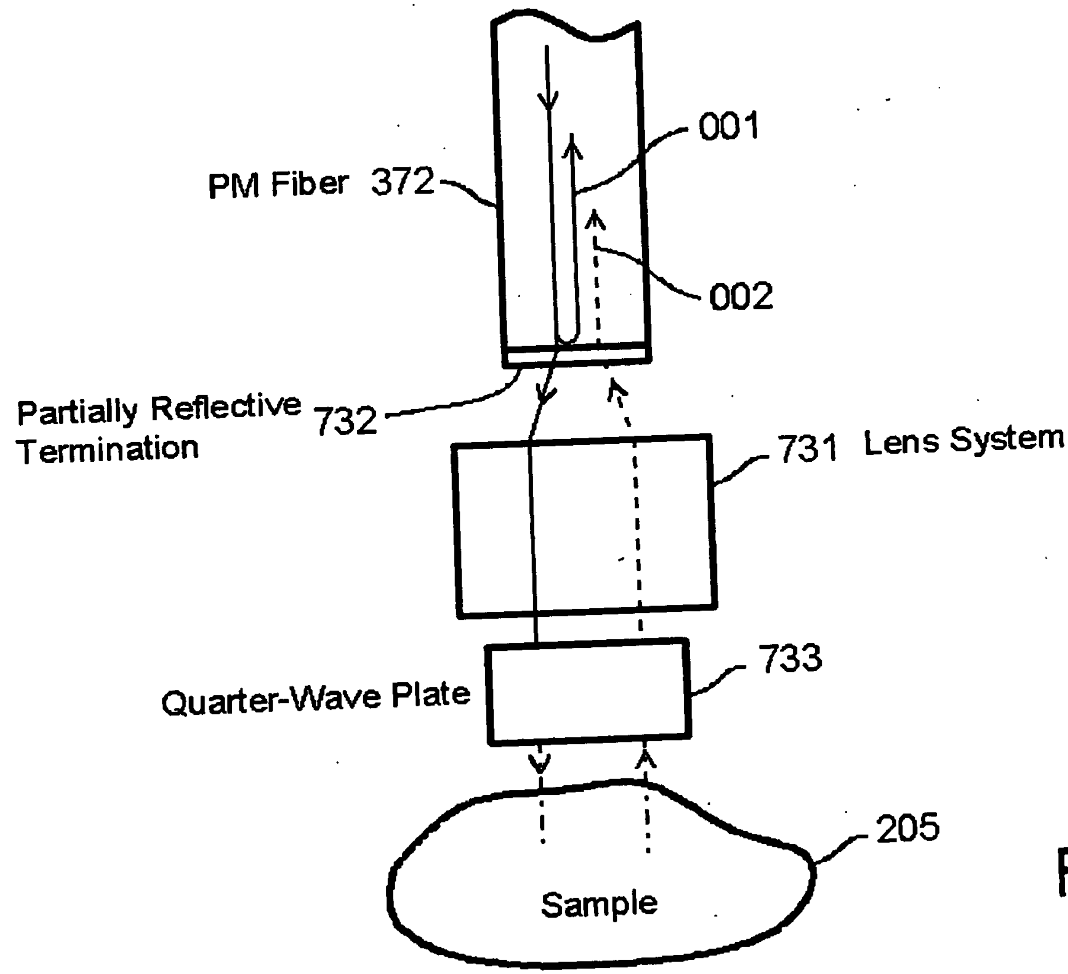
PM Fiber 1
371
610
PM Fiber 3
373
Polarization Preserving Circulator
372
PM Fiber 2
Differential Delay Modulator
250
Polarizing Beam Splitter 261
262
Detector 1
Detector 2
263
Electronic Controller
Display & Interface Module
Probe Head
631
Lens System
Partial Reflector 632
Polarization Rotator 633
205
Sample

Fig. 6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001
002
Partially Reflective Termination
732
731
Lens System
Quarter-Wave Plate
733
205
Sample

Fig. 7

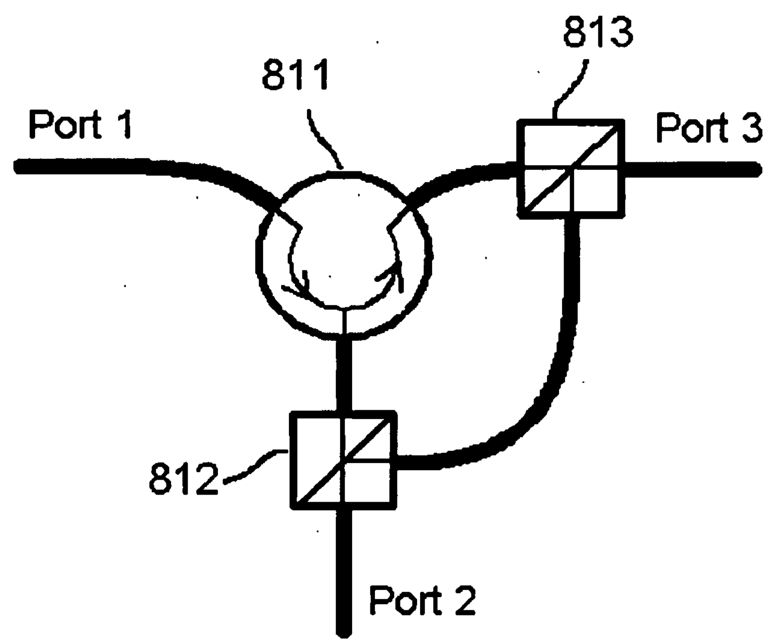
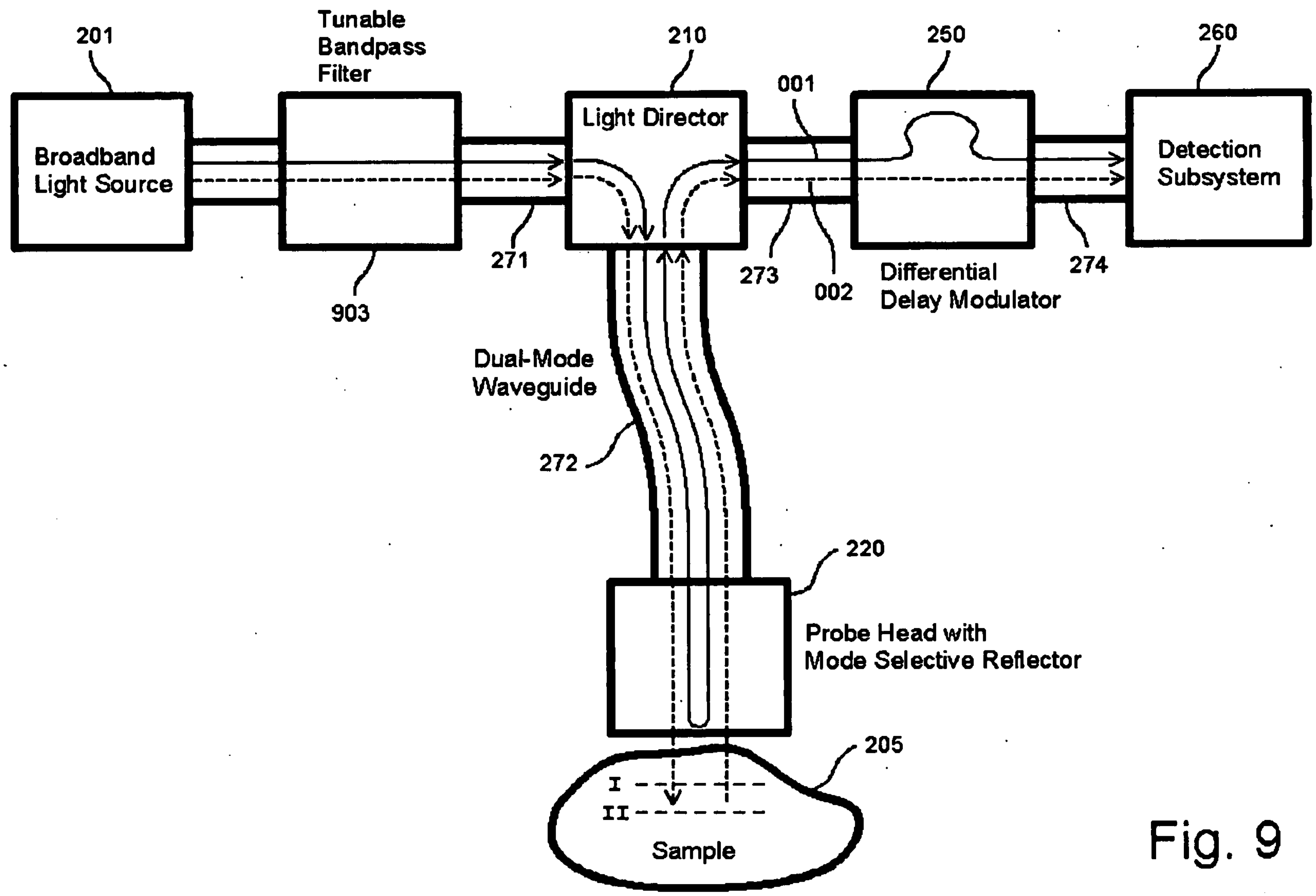


Fig. 8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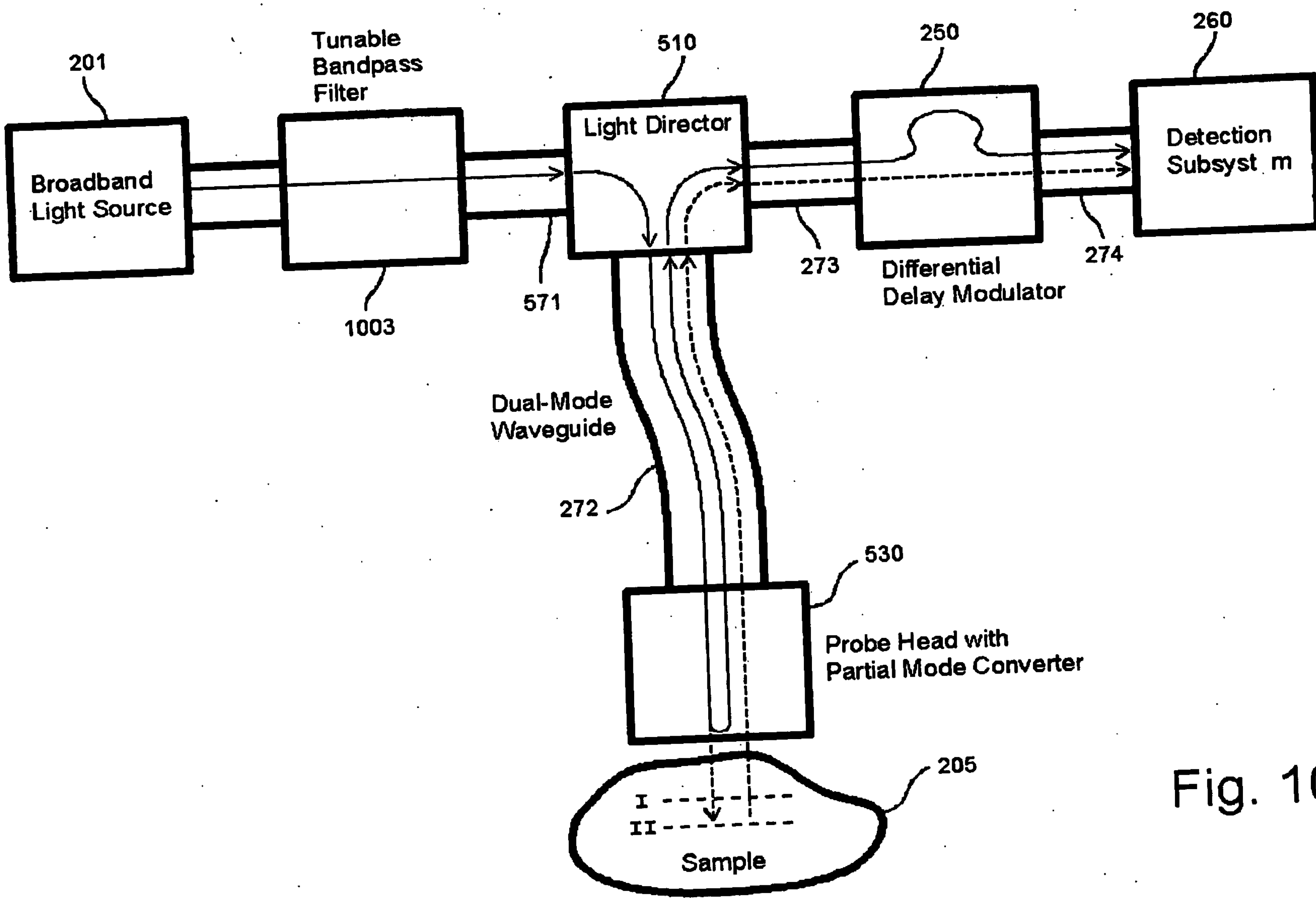
Broadband Light Source
Tunable Bandpass Filter
903
271
210
Light Director
001
273
002
250
Differential Delay Modulator
274
260
Detection Subsystem
Dual-Mode Waveguide
272
220
Probe Head with Mode Selective Reflector
205
I
II
Sample

Fig. 9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Broadband
Light Source
Tunable
Bandpass
Filter
1003
571
510
Light Director
273
250
Differential
Delay Modulator
274
260
Detection
Subsyst m
Dual-Mode
Waveguide
272
530
Probe Head with
Partial Mode Converter
205
I
II
Sample

Fig. 10

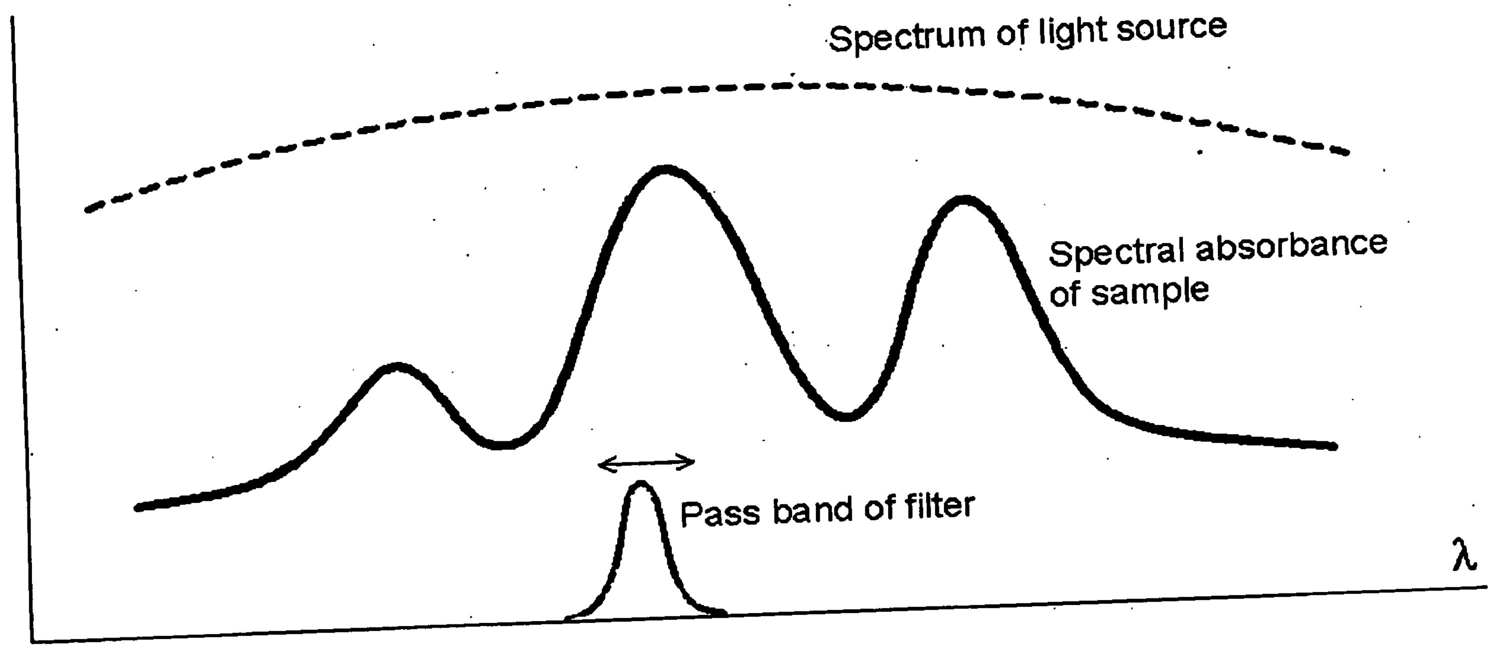
Spectrum of light source
Spectral absorbance
of sample
Pass band of filter
λ

Fig. 11

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